CONTRIBUTED PAPER

Advances in Space Traveling-Wave Tubes for NASA Missions

Used for amplifying space communications signals, these tubes continue to efficiently and reliably deliver high power and to outperform solid-state components.

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ABSTRACT | Significant advances in the performance and reliability of traveling-wave tubes (TWTs) utilized in amplifying space communication signals for NASA missions have been achieved over the last three decades through collaborative efforts between NASA and primarily L-3 Communications Electron Technologies, Inc. (L-3 ETI). This paper summarizes some of the key milestones during this period and includes development of TWTs for the Communications Technology Satellite, Cassini, and Lunar Reconnaissance Orbiter missions. Technical advances in computer modeling, design techniques, materials, and fabrication have enabled power efficiency to increase by almost 40% and the output power/mass figure-of-merit to increase by an order of magnitude during this period.

KEYWORDS | Amplifiers; cathodes; microwaves; space communications; traveling-wave tubes

I. INTRODUCTION

The traveling-wave tube amplifier (TWTA), which consists of a traveling-wave tube (TWT) mated with a high-voltage power supply, has progressed from its beginnings in the 1940s [1], [2] to become today's high-power amplifier of choice for most satellite and deep-space communication systems [3]. A schematic diagram of a TWT is shown in Fig. 1. Amplification in a TWT is attained by guiding the electromagnetic wave containing the communications signal to travel along a slow-wave circuit (such as the helix in this figure) in close proximity to an electron beam. The electron beam is provided by an electron gun consisting of a cathode, focusing electrodes, and an anode. The electrons pass through the anode and are focused into a cylindrical beam by a stack of periodic permanent magnets. The beam travels within the slow-wave circuit at a velocity close to that of the phase velocity of the electromagnetic wave. Some of the electrons in the beam are slowed by the electromagnetic field and some are accelerated. This enables the beam to form into electron bunches, which further interact with the electromagnetic wave while surrendering kinetic energy. The result is an

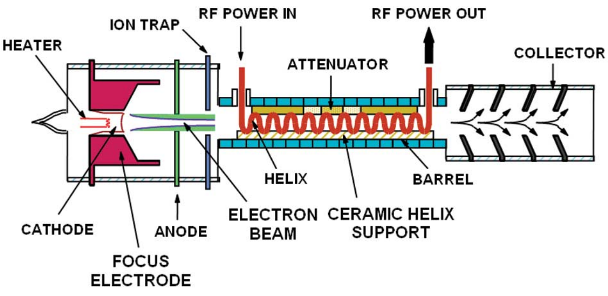

Fig. 1. *Schematic of a helix traveling-wave tube.*

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amplification of the communications signal power by a gain factor on the order of 40–50 dB. After the electrons pass through the helix, they impinge on electrodes in the collector. By decelerating the electrons, the collector is able to recover most of the remaining kinetic energy and significantly increase the power efficiency of the TWT.

The primary advantages of TWTAs with respect to solid-state power amplifiers (SSPAs) are their superior power and efficiency capabilities especially at higher microwave frequencies. While space SSPAs are typically used in the lower frequency bands below 6 GHz with radio-frequency (RF) powers of less than about 30 W, space TWTAs are used at frequencies up to more than 60 GHz with much higher power capability [4]. Despite common misperceptions, a recent data study by Boeing Satellite Systems showed that the reliability of modern TWTAs is also superior to that of SSPAs [5]. The study compared data from 30.5 million on-orbit hours of 944 SSPAs to that of 80.5 million on-orbit hours of 1783 TWTAs over a 20-year period ending in April 2004. Most of the SSPAs in this data set operated at L-band through C-band, while most of the TWTAs operated in the higher frequency Ku-band. Even with the higher frequency and power operation of the TWTAs, their reliability as expressed in failures in 10^9 h (FITs) was superior to that of the SSPAs. Using a capability metric of watt per rate of failure, the authors showed that TWTAs provided nearly six times more performance than SSPAs.

NASA and L-3 Communications Electron Technologies, Inc. (L-3 ETI, which was formerly known as Hughes Aircraft Company Electron Dynamics Division and Boeing Electron Dynamic Devices, Inc.) have played a significant role in the performance improvement of space TWTAs over the last three decades. Fig. 2 shows how the RF power capability and efficiency of L-3 ETI Ka-band space TWTs have improved over just the last 15 years. This paper will document some of the advances by NASA and L-3 ETI in design, computational modeling, and materials development that contributed to the improvement in TWT capabilities. In particular, we will discuss the areas of cathodes, coupled-cavity and helix TWT modeling, multistage depressed collectors (MDCs), and power combining.

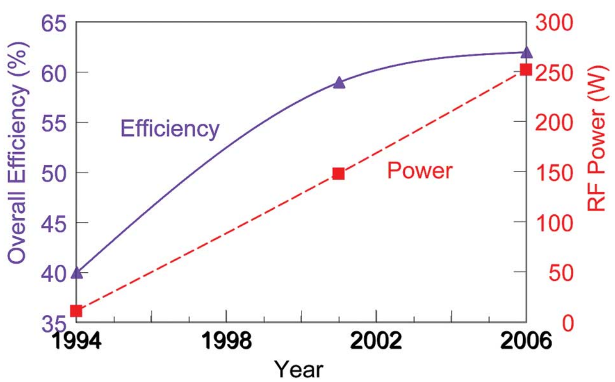

Fig. 2. ***RF output power and overall efficiency improvement in Ka-band space TWTs. Data shown are for the L-3 ETI 955H (Cassini), 999H, and 999HA models.***

II. CATHODES

Early TWTs used oxide cathodes, which were capable of long lives but had significant reliability problems [6]. These problems were overcome with the development of the M-type barium (Ba) dispenser thermionic cathode, which is now the only cathode used as an electron source in vacuum electron devices for space communications. (M-type refers to cathodes which have surface coatings containing osmium to reduce the work function and thus the operating temperature.) Thus this cathode will be emphasized here, although a large variety of other cathode types, both thermionic and nonthermionic, have been investigated over the years at NASA. The main emphasis has been to improve the understanding of the operation of these cathodes, both experimentally and theoretically, and to demonstrate reliability through cathode life tests.

The most important experimental work consisted primarily of electron emission and surface chemistry studies of Ba and oxygen (O) absorbed on refractory metal surfaces. These surfaces also contain the 5d transition elements W, Os, Ir, and alloys thereof that are typical of Ba dispenser cathodes. Surface analytical techniques such as Auger electron spectroscopy, X-ray photoelectron spectroscopy [7], and inverse photoemission [8], [9] were used. One of the significant results was the first characterization of the chemical structure of Ba and O essential for enhanced electron emission from tungsten (W) surfaces [10]. The theoretical work consisted of the first application of modern relativistic quantum chemistry to the study of the electronic structure for the interaction of Ba and O with the 5d transition metals [11]–[13]. A significant result of this effort was the explanation as to why certain 5d transition metals or alloys characteristic of M-type cathodes (Os, Ir, W-Os) displayed a lower effective work function with the adsorption of Ba and O than did pure W. The reason was shown to be the surface crystal structure (hexagonal-close-packed versus body-centered-cubic), which enabled a stronger dipole interaction.

A very significant life test was performed under contract to NASA at the Watkins–Johnson Company with M-type cathodes, which have an osmium-ruthenium coated barium impregnated tungsten matrix. The test used open anode life test vehicles designed to simulate operation in traveling wave tubes. Lifetimes of greater than 100 000 h (11.4 y) of continuous operation at 1 and 2 A/cm^2 were achieved, which demonstrated for the first time the potential of this type of cathode for long-life space applications [14].

The M-type barium dispenser cathode now used in all U.S. manufactured space TWTs is an osmium ruthenium-coated cathode produced by L-3 ETI in their recently modernized and fully qualified cathode facility. This cathode, when operated within appropriate limits of temperature and emission current density, is highly reliable and capable of lifetimes exceeding 15 y in space. The reliability of this cathode was established after extensive life testing and corroboration with models of life expectancy [6].

Another barium dispenser cathode, the reservoir cathode, with the capability of simultaneous high electron current densities and very long life, was developed under a contract with Varian Associates [15] and was the recipient of an R&D 100 award in 1987. Reservoir cathodes life tested at 2 and 4 A/cm^2 have demonstrated unprecedented stability and showed negligible degradation in electron emission after more than 100 000 h [16]. An efficient miniaturized version of the reservoir cathode has been developed [17], [18] under the NASA Small Business Innovation Research program.

III. COUPLED-CAVITY TWTs

Before 1976, satellite communication capabilities were limited by the low power levels (4–20 W) available from the space-borne traveling-wave tube amplifiers [19]. To extend communications technology to much higher power levels of transmission, the Canadian Department of Communications and NASA initiated the joint development of an experimental satellite designated the Communications Technology Satellite (CTS) in 1971 [20]. This program enabled satellite communication systems to provide enough power to broadcast directly to small, low-cost individual end receivers rather than to ground based distribution systems. For the first time communications links to different parts of Canada and the United States were established.

The development of the 12-GHz CTS TWT took place from 1972 to 1976. The Electron Tube Division of Litton Industries designed the electron gun and slow-wave circuit while NASA designed the spent beam refocuser and multistage depressed collector (MDC) [21]. This TWT, represented in Fig. 3 [22], incorporated several important design features that had not previously been used in space applications. These included:

1) an electron gun using a barium impregnated tungsten cathode;
2) a high-power coupled cavity slow-wave circuit with a velocity taper for high basic efficiency;
3) a beam refocusing section for conditioning the spent beam for entry into the collector;
4) a NASA-designed ten-stage depressed collector for high overall efficiency;
5) radiation cooling of the collector to minimize the thermal load on the satellite system.

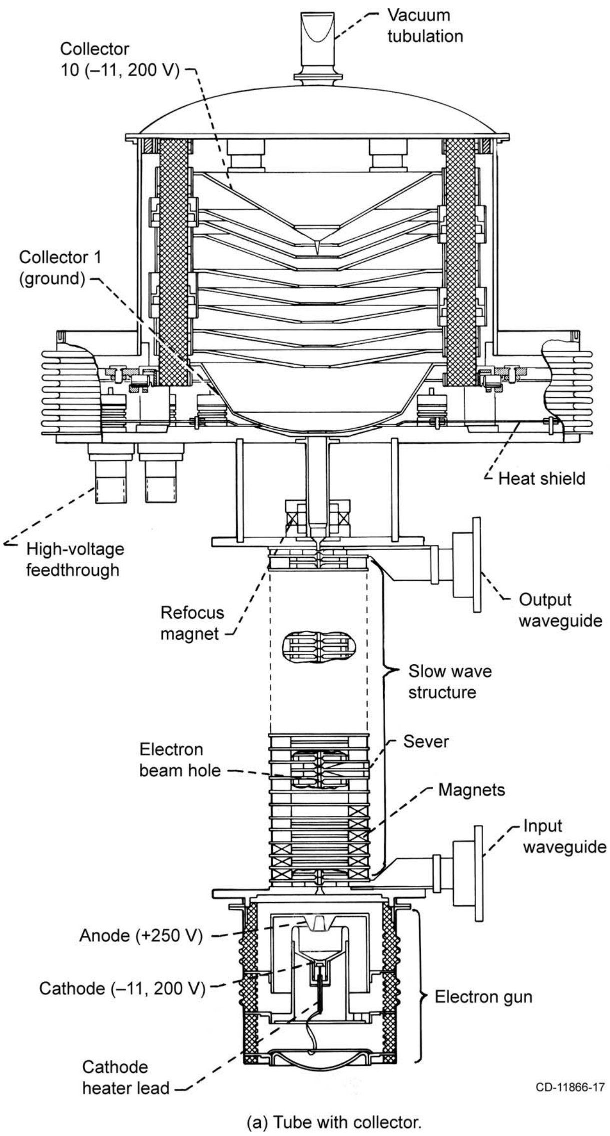

Fig. 3. *Cross-sectional schematic of Communications Technology Satellite TWT [22].*

An overall efficiency of 44.5% to 50.6% was obtained across the 12.04–12.12 GHz frequency band, the best performance reported to that date for a TWT at any frequency [22].

The 200-W CTS TWT demonstrated an increase in the power of satellite-relayed signals by a factor of ten over previous commercial satellite amplifiers and played a major role in producing the technology that made satellite television broadcasting practical. For its efforts, NASA received an Emmy Award in 1987 from the National Academy of Television Arts and Sciences [23]. The MDC technology developed for the CTS TWT was also applied to klystron power tubes used in ultra-high-frequency (UHF) TV transmitters, doubling their efficiency and making it possible for UHF stations to significantly reduce power consumption [24], [25]. This resulted in a second Emmy Award, which was presented to the Public Broadcasting System.[1]

In the 1970s, software and computational techniques for vacuum electronics design were quite crude. The design procedure for TWT components consisted of a large number of design-build-test-redesign cycles, as evidenced by the 32 builds required in the CTS program [22]. Since then, there has been a considerable effort by the vacuum electronics community in developing new software and computational techniques. This has improved the TWT design process to the point where it is now common for new high-performance TWT models to perform as predicted on the first build [26]. Both NASA and L-3 ETI have contributed considerably to this advancement in design capabilities. In this section, advancements in coupled-cavity TWT slow-wave circuit design capabilities will be outlined; in following sections, advancements in the design capabilities of helix TWT slow-wave circuits and MDCs will be documented.

The slow-wave circuit of the CTS TWT including the two-step phase velocity taper was designed with a one-dimensional coupled-cavity TWT code [27]. To more accurately model the interaction between the electron beam and the RF wave in the slow-wave circuit, NASA developed a more accurate 2 1/2-dimensional (2 1/2-D) (axisymmetric) coupled-cavity TWT code [28]–[32].

Utilizing the NASA coupled-cavity TWT model, an algorithm designated the *phase-adjusted taper* was developed to design slow-wave circuits for increased power efficiency [33], [34]. As a test case, the algorithm was applied to the CTS TWT and resulted in a phase velocity taper design that provided a computed RF efficiency 45% higher at center frequency than that of the original CTS design. Since then, more generalized algorithms based on the optimization technique of simulated annealing have been developed for designing phase velocity tapers in coupled-cavity slow-wave circuits for optimizing center frequency efficiency [35], efficiency over a wide frequency bandwidth [36], and efficiency for high-frequency circuits where dimensional tolerances are important [37].

To model the performance of a slow-wave circuit, the NASA coupled-cavity TWT model requires the geometric dimensions and cold test (absence of an electron beam) parameters for each cavity. The cold test parameters, which include the RF phase shift, interaction impedance, and attenuation, were traditionally obtained experimentally. In the early 1990s, techniques were developed to calculate these parameters with three-dimensional (3-D) electromagnetic codes [38], [39]. By combining these techniques with the NASA coupled-cavity TWT code, it was shown that RF output characteristics could be accurately obtained computationally without dependence on expensive and time-consuming experimental cold test procedures [40]. These computational techniques made it possible to investigate not only conventional coupled-cavity TWTs but also helical TWTs (next section) and novel circuits such as the TunneLadder TWT [41] and the Finned-Ladder TWT [42].

IV. HELIX SLOW-WAVE TWTs

A TWT with a helix slow-wave circuit cannot provide as much RF output power as one with a coupled-cavity circuit but can have a much broader frequency bandwidth [43]. As in coupled-cavity TWT circuits, phase velocity tapers are commonly used to increase power efficiency. The dynamic velocity taper is a velocity taper developed at NASA [44] that not only increases power efficiency but also improves the linearity of the output power with respect to the input power [45]. This is important for reducing distortion in communications applications.

As with coupled-cavity circuits, the development of 3-D modeling techniques has enabled helix circuits to be modeled accurately [46], [47]. These 3-D models have helped to enable first-pass TWT design capabilities, resulting in considerable savings in time and cost [48], [49]. Additionally, they have enabled the investigation of manufacturing tolerance effects on TWT performance [50], magnetic focusing [51], and intersymbol interference [52].

The Ka-band TWT developed by Hughes Electron Dynamics Division (now L-3 ETI) and NASA for the Cassini mission to Saturn started out as a research project to incorporate the newly developed helix and collector design methods and to use textured electrodes in the MDC [53], [54]. Textured electrodes are high-voltage electrode stages that are roughened or "textured" to produce spires or peaks with an average feature height and separation of approximately 10 and 5 μm, respectively [55]. The surface texturing suppresses secondary electrons, which increases the current collected and improves MDC efficiency. The TWT produced 10.7 W of RF output at 32 GHz with an overall efficiency of 40.2%. The TWT has been used in radio science experiments [56], a search for gravitational waves [57], and an experiment to test general relativity [58].

From 2001 to 2004, L-3 ETI (then Boeing Electron Dynamics Devices, Inc), under a NASA contract, developed the 999H TWT model designed for deep space Ka-band communications in the 31.8–32.2 GHz downlink frequency band with a 12-y operating lifetime. This TWT demonstrated 143.5 W of continuous-wave RF power with 60% overall efficiency, both records for Ka-band space TWTs. Following the 999H TWT, L-3 ETI developed the higher power Model 999HA TWT under another NASA contract in 2004–2005 [26]. This Ka-band space TWT shown in Fig. 4 was developed to provide high-rate high-capacity direct-to-Earth communications for science data

[1]http://www.emmyonline.org/docs/engineering_award_winners_rev3.pdf.

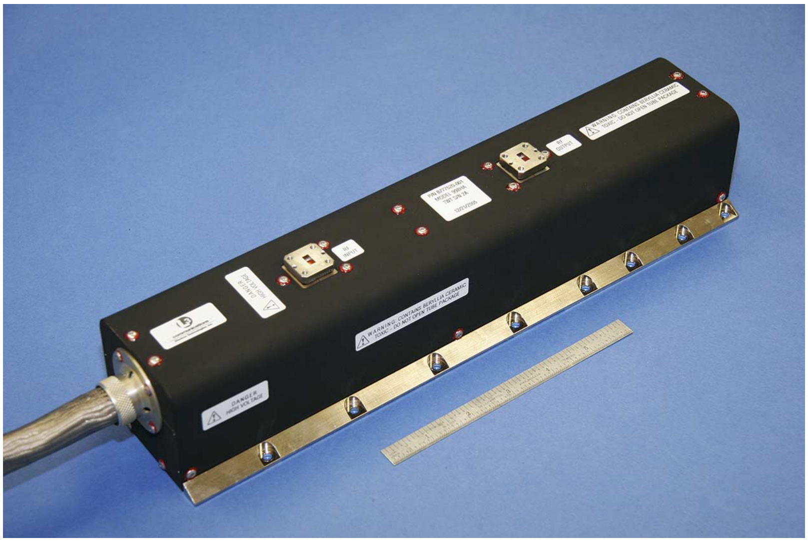

Fig. 4. ***Photograph of L-3 ETI model 999HA Ka-band TWT.***

and video from NASA deep space planetary orbiters with a 7-y operating lifetime. It has demonstrated 252 W of continuous-wave output power over the 31.8–32.3 GHz frequency band with 62% overall power efficiency. This represents a 75% increase in power over the previous 999H model with a further improvement in overall efficiency. Additionally, the TWT is operational over a very wide frequency bandwidth of 9 GHz. This flexibility will enable this TWT to be utilized for a large number of future NASA deep-space missions. The key innovations in this TWT include:

1) the design of a dual-anode isolated focus electron gun, which enables excellent focusing over a wide range of voltage and current values, providing the flexibility of operation over a wide range of output power;
2) the advanced design of the periodic permanent magnet stack surrounding the slow-wave circuit, which was also important in maintaining excellent focusing of the electron beam;
3) the advances in computer modeling techniques utilizing the U.S. Naval Research Laboratory's CHRISTINE 3-D code [59], which enables a high-efficiency slow-wave circuit design that is stable with respect to backward wave oscillations over a wide range of input power levels;
4) the advances in computer modeling techniques utilizing the U.S. Naval Research Laboratory's MICHELLE 3-D code [60], which enables a high-efficiency four-stage depressed collector design, resulting in improved conduction cooling and thermal reliability;
5) the advanced design of the input and output windows (through which the RF signals pass into and out of the slow-wave circuit), which enables the TWT to operate over a wide range of frequencies;
6) redesigned high-voltage feedthroughs, which enable improved electromagnetic interference shielding.

The result of these advances enabled the mass of the 999HA TWT to be decreased to only 1.5 kg, compared to 2.3 kg for the 999H TWT and 11.9 kg for the CTS TWT. In addition, the need for a 1.2-kg Faraday cage for electromagnetic interference shielding has been eliminated. The L-3 ETI 999HA TWT was recognized with a 2006 R&D 100 Award. It is the baseline TWT from which lower power Ka-band TWTs for the Kepler and Lunar Reconnaissance Orbiter (LRO) are being designed. Previous to the development of the L-3 ETI 999H and 999HA TWTs, the highest power Ka-band space TWT was a 35-W model with an overall efficiency of 46%, which was developed by Thales Electron Devices GmbH and is currently flying on the NASA Mars Reconnaissance Orbiter mission [61].

Future deep-space missions may require combining TWTs to obtain even higher RF power. A high-efficiency two-way power combiner waveguide circuit based on a magic-T hybrid junction and two 100-W Ka-band helix (Model 999H) TWTs was designed and developed as a potential high-power RF source. Power-combining efficiencies of over 90% and a high-data-rate capacity of 622 Mbps with quadrature phase-shift keying modulation were demonstrated [62]–[64]. Fig. 5 [64] shows the individual and combined RF powers over a 1-GHz bandwidth. Several waveguide hybrid junction geometries for greater power handling and transmission efficiency have been designed [65].

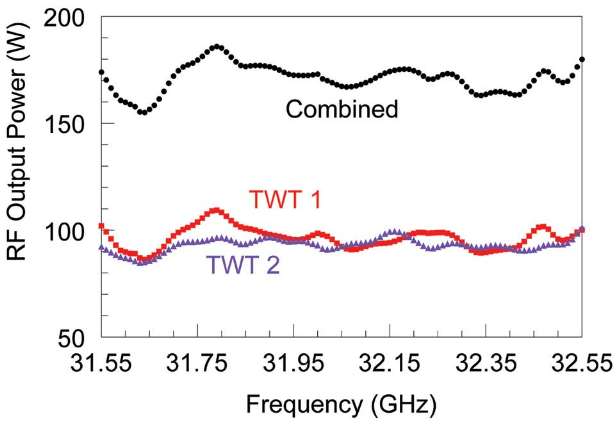

Fig. 5. ***Individual and combined RF output power for two-way power combiner waveguide circuit with a magic-T hybrid junction [64].***

V. COLLECTORS

The fundamental purpose of the collector is to dispose of the electron beam after it traverses an RF structure. Originally the potential of the collector electrode was set equal to or higher than the potential of the body (or RF structure) of the tube. As early as 1940, it was shown that by setting the collector electrode at potentials lower than the beam voltage, or depressing the potentials, one can increase overall efficiency [66]–[68]. The depressed collector decreases the velocity of the electrons before they strike the collector surface. This, in turn, produces significant power savings by reducing the thermal load and "recovering" power.

The success of the single stage depressed collector led to the development of the multistage depressed collector (MDC) [68]–[70], which resulted in further improvements in overall efficiency. By using several symmetric or asymmetric depressed electrodes, electrons are sorted by velocity. The slowest electrons are collected at the highest potential electrode, next slowest at the next highest potential, and so on. By sorting electrons, there is a greater chance for significant deceleration of the entire spent electron beam. This process is also referred to as "power recovery" to describe the conversion of the electron beam's kinetic energy to potential energy as the electrons slow down before hitting the collector.

The next significant leap in MDC design was due to the advent of analog and digital computers. In a series of contracts, NASA applied analog computers to MDC design [71]–[73]. The dispersive lens collector (DLC) used in the CTS TWT was created to provide one general design that is applicable to many tube types and modulation levels by changing only the individual aperture sizes [74]. As digital computers became more powerful, they eventually surpassed analog computers as MDC design tools [75], [76]. Digital computers also gave the designer more freedom to choose location, aperture size, and number of electrodes. NASA pioneered the use of an axisymmetric ray tracing code for 2 1/2-D MDC design that has been successfully used since 1979 [76].

Despite its accuracy, the 2 1/2-D design method was lacking in two areas. Since the ray-tracing code was axisymmetric, it could only be applied as an approximation to the analysis of asymmetric collectors. In addition, the code was a steady-state solver that could not use any phase space information associated with the spent beam mode. To address these deficiencies, NASA pioneered the use of a 3-D particle-in-cell code that was typically used for accelerator applications, in the analysis of MDCs [77]. While this method was computationally demanding, it provided new insight in MDC operation and showed more accuracy than the 2 1/2-D method.

The efficiency of collectors is affected by the material of the collector and the secondary electron emission properties of its surface. Secondary electrons are generally divided into three groups: true secondaries, with energies from near zero to several tens of electron volts; inelastically scattered secondaries, with energies higher than true secondaries but lower than the energy of the incident electron beam; and elastically scattered (energetic) secondaries, with energies near the energy of the incident electron beam. All secondary electrons can decrease collector performance. If a secondary electron strikes an electrode, it increases the kinetic energy at that electrode, thereby decreasing collector efficiency. Energetic secondary electrons are particularly important because their high energies give them a greater chance of leaving the collector, reentering the slow-wave circuit, and producing undesired signal distortion or oscillation.

To address these concerns, NASA investigated the secondary emission properties of various materials for use in collectors, including polished copper, textured copper, and isotropic graphite. Traditionally, the most common collector material has been copper. It has been chosen for its mechanical properties and high thermal and electrical conductivity. However, copper has the disadvantage of a relatively high secondary electron yield for the electrons scattered from the surface of the collector. Another material that has been studied and used to manufacture collectors is carbon, with various forms of carbon either brazed or deposited on copper [78], [79]. Most forms of carbon, including soot and pyrolytic carbon, have very low yield of secondary electrons. This yield can be further reduced with a texturing process [80]. During the Cassini TWT development effort, it was shown that the TWT with textured copper MDC electrodes consistently demonstrated significantly higher (41.9%) overall efficiency than the TWT having untreated copper electrodes (36.0%) and somewhat higher than the TWT with graphite electrodes (39.5%) [55]. NASA investigations also showed that energetic secondary electrons have a complex angular distribution that is strongly dependent on the energy and angle of incidence of the electron beam, as well as the atomic number and surface morphology of the material [81]. These data provided a more complete and accurate model of ESS electrons, enabling more simulation accuracy and more insight into collector design.

VI. CONCLUSIONS

Significant advances in the performance and reliability of traveling-wave tubes utilized in amplifying space communication signals for NASA missions have been achieved over the last three decades through collaborative efforts between NASA and primarily L-3 Communications Electron Technologies, Inc. There has been a tremendous improvement in space TWTs from the 12-GHz 200-W CTS coupled-cavity TWT in 1976 to the 32-GHz 250-W L-3 999HA helix TWT in 2006. With similar output power at a higher frequency, the 999HA is 1.39 times as efficient with a decrease in mass of almost a factor of eight. Because of their high-power capability, high efficiency, and reliability record, TWTs are expected to continue to be essential in the foreseeable future for space communications.[2] ■

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